



**ontario hydro
research division**

TO: Mr. W.R. Collard
Manager
Electrical Controls Engineering
Design and Development - Gen
H13A27

**PRELIMINARY ANALYSIS OF CONTROL CABLE
RESPONSE TO LIGHTNING DISTURBANCES
AT A NUCLEAR POWER STATION**

S.M. Harvey

Because of the single-point grounding and shielding practices used in generating stations, circuit conductors in control and annunciation cables extending outside the powerhouse must rely on the conductivity of the earth or nearby bonding conductors for protection from lightning-related electrical disturbances. Tests carried out at Bruce NGS "B" have shown that the response of long interbuilding cables to broadband disturbances is a complicated function of frequency. Preliminary laboratory tests and modelling exercises have been carried out to explore the functional dependence of the frequency response on cable and site parameters. Further refinements will be required before practical engineering guidelines for electromagnetic compatibility can be developed.

1. INTRODUCTION

Following reports of lightning-related electrical and instrumentation faults, an investigation of the on-site wiring and grounding at Bruce NGS "B" was requested by Electrical Controls Engineering Department. A preliminary site visit, carried out by Electrical Research Department in the fall of 1989, implicated the power and control cables running in underground ducts between the powerhouse and outbuildings containing the standby generators SG5 and SG6. It was hypothesized that a lightning stroke near these buildings produced a large current in the grounding grid between the standby generators and the powerhouse, resulting in a high ground potential difference (GPD) and induced interfering voltages and currents on the power and control cables.

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Two recommendations were made: (a) to install additional ground grid bonding conductors, including two to run close to the control cables between the powerhouse and the standby generators SG5 and SG6, and (b) to document for future reference the effect of the additional conductors on broadband voltages and currents induced on the interbuilding cables.

The work was completed in the spring of 1990 and is described in a Research Division report/1/. The additional bonding and shielding conductors were found to be moderately beneficial, reducing test voltages and currents on buried control cables by an average factor of about 3.

A proposal was subsequently submitted by Electrical Research for a multi-stage study, over a frequency range representative of lightning disturbances and switching transients, of grounding grid transient voltage rise, and shielding and grounding practices for long cables. Stage 1, to include preliminary laboratory tests and modelling exercises of the frequency response of control cable samples, has now been completed. In this work, the focus has been primarily on exploring the functional dependence on cable and site parameters, rather than on detailed mathematical treatment.

2. STUDY RATIONALE

It is unusual for lightning to cause damage to bonding or grounding conductors, or other wiring. However, if a small fraction of the energy contained in the lightning stroke finds its way via these conductors onto the terminals of sensitive electrical equipment, then equipment malfunction, blown fuses, or damage may result. The path may be complex and, in extended wiring systems, may not be traceable. The task then is to identify possible weak points in the available paths and to strengthen them.

In a large power station, five general methods for avoiding a lightning-related interference problem may be identified.

- (1) *Avoid the source.* If possible, prevent the lightning strike or divert the current away from the station grounding grid and other conductors.
- (2) *Lower the grounding grid impedance.* Ensure grounding grid integrity and arrange the bonding and grounding conductors for lowest point-to-point inductance. This will lower the ground potential differences (GPDs).
- (3) *Shield the wiring and cabling.* Provide adequate bonding conductors, arranged to provide inductive neutralization (shielding) of induced voltages, along each cableway or wireway that is exposed to GPD.
- (4) *Reduce intercircuit coupling.* Segregate exposed wiring from wiring that may be connected to sensitive equipment, especially on cable distribution frames, etc.
- (5) *Protect the equipment.* Specify adequate equipment immunity or install surge arresters, filters, or other protective devices at the terminals of sensitive equipment.

The preliminary inspection at Bruce NGS "B" showed that the interbuilding cables were placed underground and, in the case of the control cables, were enclosed in steel ducts. However, the ground grid conductors were widely spaced and the cable shields were connected to ground only at one end in conformity with the single-point grounding practice in the powerhouse. These practices raised concerns that large voltages could be developed between the ungrounded ends of the cables and locally grounded equipment in the event of a lightning strike.

The subsequent investigation, focusing on methods 2 and 3, demonstrated in a qualitative way that cable voltages could be reduced by the effective use of bonding and shielding conductors, without having to install costly lightning prevention or diversion systems of dubious potential, or having to rewire or redesign existing power and control systems. While the reductions effected on the Bruce NGS "B" control cables were sufficient to substantially mitigate the lightning threat, it was clear from the measurements that the effect of shielding conductors on underground cables was not well understood.

The present study was proposed in order to generate more information on the effectiveness of shielding and grounding practices used for long control and annunciation cables. The information is intended to help designers in evaluating the benefits of various changes to grounding systems and low voltage wiring.

3. GPD INDUCED INTERFERENCE ON ELECTRICAL CABLES

The general problem of interfering voltages and currents produced on electrical wires and cables by GPD is shown in Figure 1. If a current I is injected into the ground grid at one point, and exits to earth at a remote location or locations, then a ground potential difference V_{AB} will be produced between two arbitrary points A and B on the ground grid. In the following, the GPD will be represented simply by V_G .

An insulated conductor installed between points A and B with the end at point A bonded to the grid, will experience a voltage between the open end of the conductor and point B. This voltage is sometimes called a "transferred" voltage V_T . The ratio V_T/I may be defined as a transfer impedance Z_T .

In the low-frequency limit, V_T will become equal to V_G , and V_G will in turn become equal to the IR drop between the points A and B. Thus the transfer impedance is equal to the resistance R . At power frequencies, satisfactory models have been developed that take into account the resistance of the earth and the reactive impedance of the ground grid conductors.

In the frequency range between a few kHz and a few MHz, the transfer impedance for installations of power-station size becomes a complex function of the system's electrical parameters. These parameters include the high-frequency dielectric properties of the earth and other materials, the layout of both the ground grid and the electrical wiring, and the natural resonant frequencies of the conductors. The resonant frequencies of a conductor that is grounded at one end and open at the other (single-point ground) are given by

$$f = (2n - 1)c/(4\ell), \quad (n = 1, 2, 3, \dots), \quad (1)$$

where ℓ is the length of the conductor and c is the propagation velocity as determined by the electrical properties of the surrounding medium. Frequencies less than one quarter of the first resonant frequency (plotted in Figure 2 for a range of lengths and dielectric media) may be considered to lie in the subresonance range. In this range, the transfer impedance may be modelled with lumped-element equivalent circuits. Higher frequencies require some form of distributed circuit parameters or transmission line theory.

Figure 3 shows the transfer impedance for one 520 m long conductor (a control cable shield) running between the Bruce NGS "B" powerhouse and the standby generators, measured over the subresonance and resonance regions. The transfer impedance was measured before and after the installation of the additional bonding conductors.

4. ANALYSIS OF SUBRESONANCE RESPONSE

In the subresonance frequency range, modelling exercises are fairly straightforward and laboratory tests can be performed without the necessity of replicating the physical layout of an actual cable installation. Some comparisons between theory and experiment are given below.

4.1 Single-point-ground Conductors

The functional response to a GPD disturbance of a single-point grounded conductor may be modelled in terms of the lumped-parameter equivalent circuit shown in Figure 4, from which,

$$V_T/V_G = [R + j\omega(L - M)]/[R + j\omega L], \text{ and} \quad (2)$$

$$Z_T = R + j\omega(L - M). \quad (3)$$

For the simple case of two parallel conductors of equal length ℓ in air, L and M can be calculated to a good approximation from the formulas given below/2/

$$L = 2 \times 10^{-7} \ell (\ln 4\ell/d - 0.75)$$

$$M = 2 \times 10^{-7} \ell (\ln 2\ell/D - 1 + D/\ell)$$

$$L - M = 2 \times 10^{-7} \ell (\ln 2D/d - D/\ell + 0.25),$$

where d is the conductor diameter and D is the separation.

The computed value of Z_T for a 100 m long single-point grounded conductor parallel to a similar length of current carrying conductor is plotted in Figure 5 for two different separation distances. The Figure shows that the transfer impedance rises rapidly above a frequency of about 1 kHz due to the inductive term ($L - M$). The magnitude of the inductive term is reduced by bringing the two conductors closer together, due to inductive neutralization. For this reason, bonding and grounding conductors that are located close to electrical wiring are sometimes referred to as shielding conductors (but not, technically, as shields). Figure 5 demonstrates good functional

agreement with the measured data from Bruce NGS "B" (Figure 2) up to about 15 kHz, and correctly predicts the reduction of Z_T in this frequency range due to the addition of bonding conductors close to the cables.

The extension of the equivalent circuit of Figure 4 to include a larger network of grounding grid conductors and a more complex geometry is fairly straightforward. However, a detailed knowledge of the actual cable geometry, the distribution of injected current among the ground grid conductors, and the effect of earth resistivity on the lumped-circuit parameters would be required in order to obtain quantitative agreement with experiment.

4.2 Shielded Cables

The extension of the above subresonance model to the important case of conductors that are enclosed within a current-carrying cable shield is made in a separate report/3/. It is clear that a cable shield, if it is grounded at both ends, will perform the function of a shielding conductor as described in section 4.1. However, because the circuit conductors are enclosed within the shield conductor, the inductive term ($L - M$) can be made very small, or even zero. A bonding or grounding conductor that fully encloses the electrical wiring is properly referred to as an electromagnetic shield.

Figure 6 shows some laboratory measurements of the subresonance conductor-to-shield transfer impedance for four different types of shielded cable, each 21.5 m long. Cable D, with a cylindrical shield, is an example of parallel conductors having essentially complete inductive neutralization, the mutual inductance M being equal to the self inductance L . Cables A, B, and C are examples of cables with spiral shield geometry and consequently reduced mutual inductance between the shield and the core conductors. The intermediate slopes observed for cables B and C are thought to result from imperfect contact between the spiral turns of the shield.

5. ANALYSIS OF RESONANCE RESPONSE

Any conductor that is exposed to lightning-related GPD and that is more than 20 or 30 m long may be subject to resonance conditions. A number of computational models exist for calculating the resonance response of a conductor exposed to a broadband electrical disturbance. However, the calculations can become quite complicated and the necessary propagation and loss parameters are generally unknown. Electrical Research has carried out some work on modelling the resonance response of uniform lengths of shielded control cables/4/, but has not yet attempted to model actual control cable installations.

In order to provide a controlled environment for testing resonance responses, a special test facility, shown schematically in Figure 7, was set up in the basement span room of the KR building. A current-carrying ground grid was simulated with a 27 m length of cable tray attached to one wall of the room, while a second cable tray, about 0.5 m above the first, was used as a current return. Characteristically, such a system will have resonance frequencies of its own that will "colour" any wire or cable responses measured in the system. To minimize these resonances, a 100 ohm non-inductive resistor, selected to give the lowest voltage standing wave ratio

(VSWR), was connected between the trays at the end remote from the current source. With the available hardware, a reasonably satisfactory VSWR of about 4:1 was achieved.

5.1 Single-point-ground Conductors

The extension of equation (3) into the resonance region may be written as

$$Z_T = \frac{(Z_0/I) \int_0^l I(z) Z_T(z) [Z_0 \cosh \gamma z + Z_1 \sinh \gamma z] dz}{(Z_0 Z_1 + Z_0 Z_2) \cosh \gamma l + (Z_0^2 + Z_1 Z_2) \sinh \gamma l}$$

where Z_1 and Z_2 are the impedances of the grounded and open ends of the line respectively, and Z_0 is the line's characteristic impedance (assumed constant). $Z_T(z)$ and $I(z)$ are the incremental transfer impedance (equation 3 redefined for incremental lengths) and source conductor current at a distance z along the line, and γ is the propagation constant. The current I is the source conductor current at a suitable reference location. The calculated response for a uniform lossless line having a length of 21.5 m and a propagation velocity of 0.7 times the free-space velocity is shown in Figure 8.

Experimental data were collected by laying cables A to D (described in section 4.2) in the lower cable tray and measuring the transferred voltage V_T at the open end of each cable (switch S of Figure 7 in position 1) as a function of frequency over the first two conductor resonances. Curves were generated for V_T/I and V_T/V , where I and V are the source current and voltage, respectively, measured at the source end of the test facility. The measured transfer impedances for cables A and D are shown in Figure 9. The frequency response of these cables is functionally similar to that calculated for the standard transmission line.

This functional agreement does not extend to the Bruce data. The resonance peaks shown in Figure 8, recalculated for a 520 m cable, occur at frequencies of 100 kHz and 300 kHz. Comparison with Figure 2 shows that the Bruce cable does not display characteristic resonance peaks at these frequencies. The distinguishing resonance-region features of the transfer impedance in Figure 2 are a broad peak at 40 kHz and a sharp resonance-type drop in the transfer impedance at 80 kHz, followed by a gradual falloff at higher frequencies. Resonance region features are not significantly affected by the installation of additional bonding conductors.

The lack of functional agreement clearly demonstrates the need to identify and take into account a variety of site-specific factors when modelling the resonance region response of long interbuilding cables, and suggests that the effect of these factors on high-frequency cable response is greater than the effect of parallel shielding conductors. Such factors could include the high-frequency dielectric and loss characteristics of the earth, the magnetic properties of the ferrous cable ducting, the attenuation due to long conductors, and the variable conductor geometry in the vicinity of the cable path. The development of improved models and better information on the

electrical properties of the generating station environment will be required in order to quantify their relative importance.

5.2 Shielded Cables

The span room test facility was also used to extend the measurements of shielded cables (switch S in position 2) into the resonance region. With the cable shield grounded at both ends, the transferred voltages were quite small and were found to be very sensitive to the limitations of the test facility. Consequently, they have not yet been analysed in any detail. Qualitatively, transfer impedance reductions of up to a factor of 1000 were observed, thus confirming the superior performance of cylindrical shielding conductors at resonance frequencies.

As reported previously/1/, the control cable transfer impedance at Bruce NGS "B" was reduced by a factor of about 10 when the cable shield was grounded at both ends. Part of the discrepancy can be attributed to the long bonding conductors used to connect cable shields to distribution frame grounds at Bruce NGS. The effect of other site-specific factors cannot adequately be modelled at this time.

6. **SUMMARY**

A preliminary study of control cable response to broadband lightning-type disturbances has been initiated, with a view to developing improved guidelines for cable installations in generating stations. A control cable response measured at Bruce NGS "B" has been evaluated in terms of its functional dependence on frequency and on the proximity of ground-grid bonding conductors, through the use of laboratory simulations and simple computational models. The general findings are summarized below.

- As a result of a rather sparse ground grid, combined with single-point grounding and shielding practices in the powerhouse, interbuilding cables at Bruce NGS "B" are exposed to lightning-induced high-frequency disturbances without effective electromagnetic shielding, other than that provided by an earth cover.
- The most effective electromagnetic shielding consists of a concentric cylindrical bonding or grounding conductor, such as a continuously bonded metallic conduit or cable shield, within which the cable conductors are enclosed. Failing this, the grounding grid design can provide some electromagnetic shielding. Bonding and grounding conductors placed close to the cables are more effective than those placed farther away.
- The response of long interbuilding cables to an electromagnetic disturbance may be modelled at low to intermediate frequencies with lumped-component equivalent circuits. The upper frequency limit for such models is inversely related to the length of the cable. For quantitative agreement, the circuit parameters must be calculated from the known physical layout, the dielectric properties of the soil, and other relevant quantities.

- For cables more than 20 or 30 m in length, the response to lightning-related disturbances will include the high-frequency or resonance region. In this region the response is properly modelled by means of transmission line theory. While the tests at Bruce NGS "B" do show resonance type features, the results do not functionally agree with standard transmission line models.
- Discrepancies can be attributed to site specific factors such as the resistivity and dielectric properties of the earth, ground grid design, or cable routing and installation practices. Practical engineering guidelines for effective protection of exposed interbuilding cables will require a better understanding of these and other factors that affect the response of the cables to broad-band electromagnetic disturbances.

Approved by:

A.F. Baljet

ub A.F. Baljet
Manager
Electrical Research Department

Submitted by:

S.M. Harvey

S.M. Harvey
Senior Physicist
Science Section
Electrical Research Department

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2. Inductance Calculations. Van Nostrand, 1946. F.W. Grover.
3. The Effect of Mechanical Construction and Grounding Practices on the Performance of Control Cable Shields. Research Report 89-279-K. S.M. Harvey.
4. This work, by D.A. Barrow, exists in draft form but has not been issued as a report.

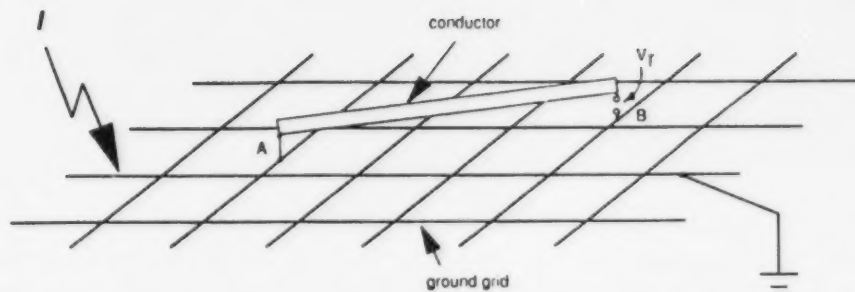


Figure 1 Example of an insulated single-point-ground conductor influenced by a network of current-carrying conductors.

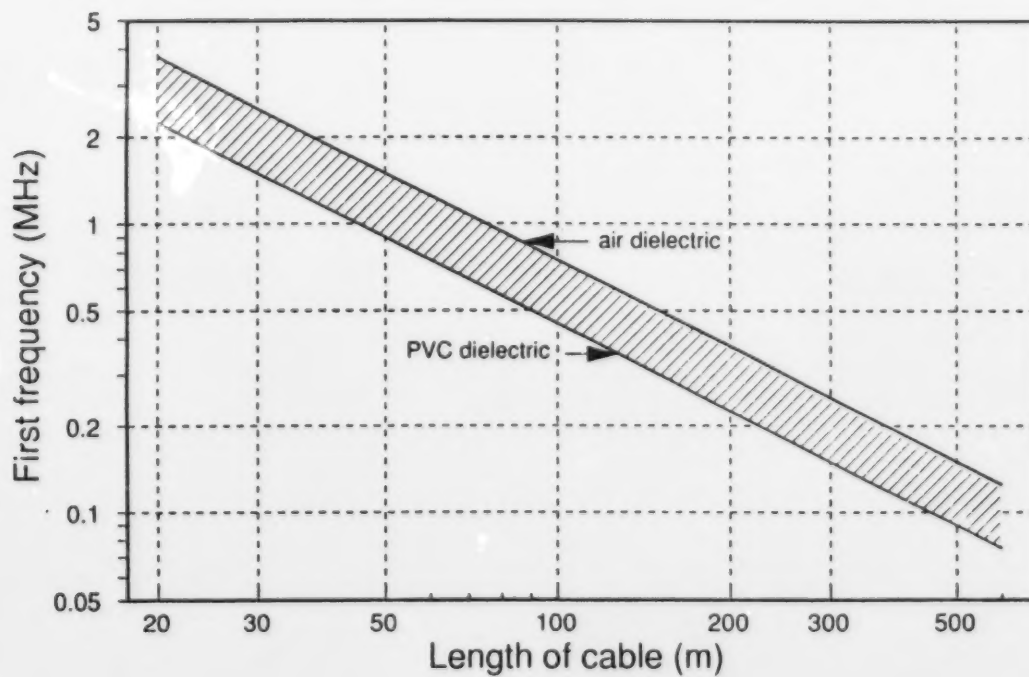
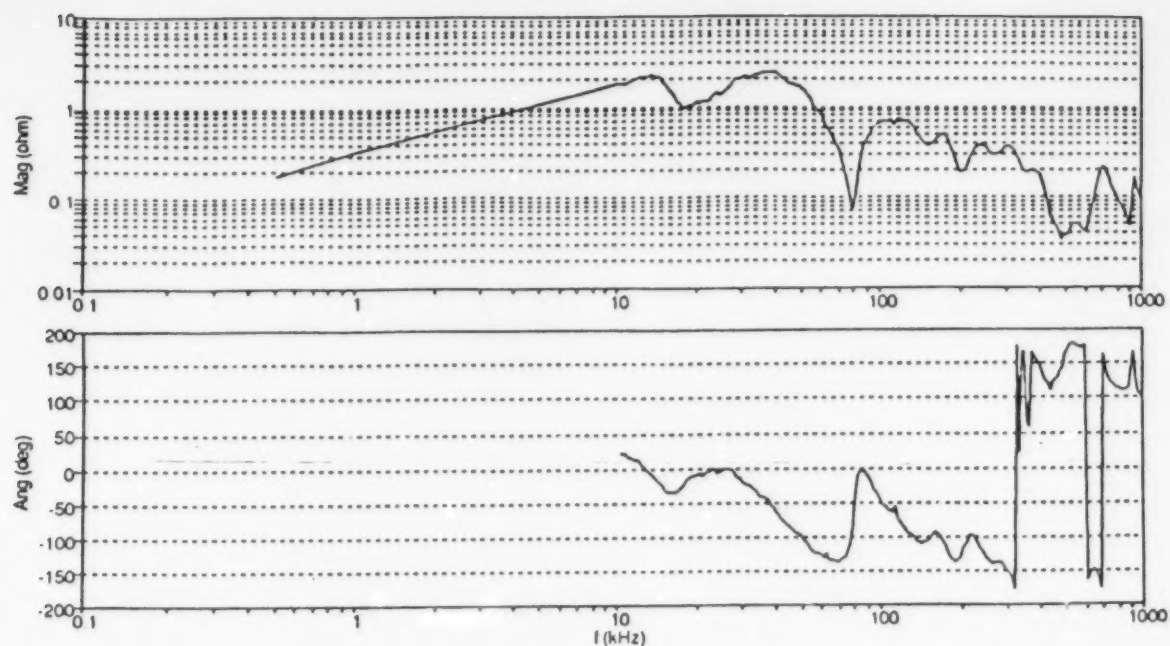
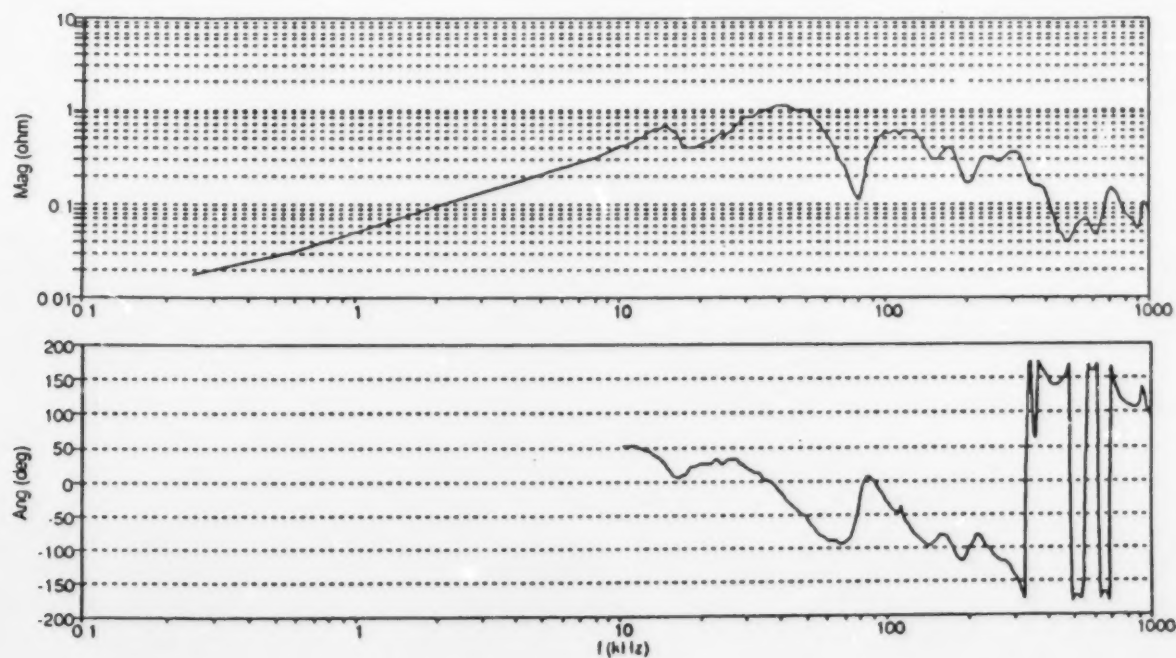


Figure 2 Resonance frequency of a single-point-ground conductor as a function of length and insulating medium.



(a) Original grounding



(b) With additional bonding wires

Figure 3 Transfer impedance measurements made on a 520 m control cable at Bruce NGS "B" (from Research Report 90-141-K).

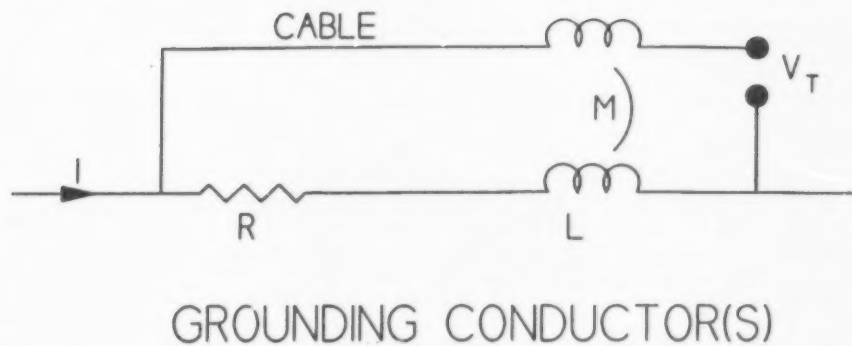


Figure 4 Simplified lumped-circuit schematic of the conductors shown in Figure 1.

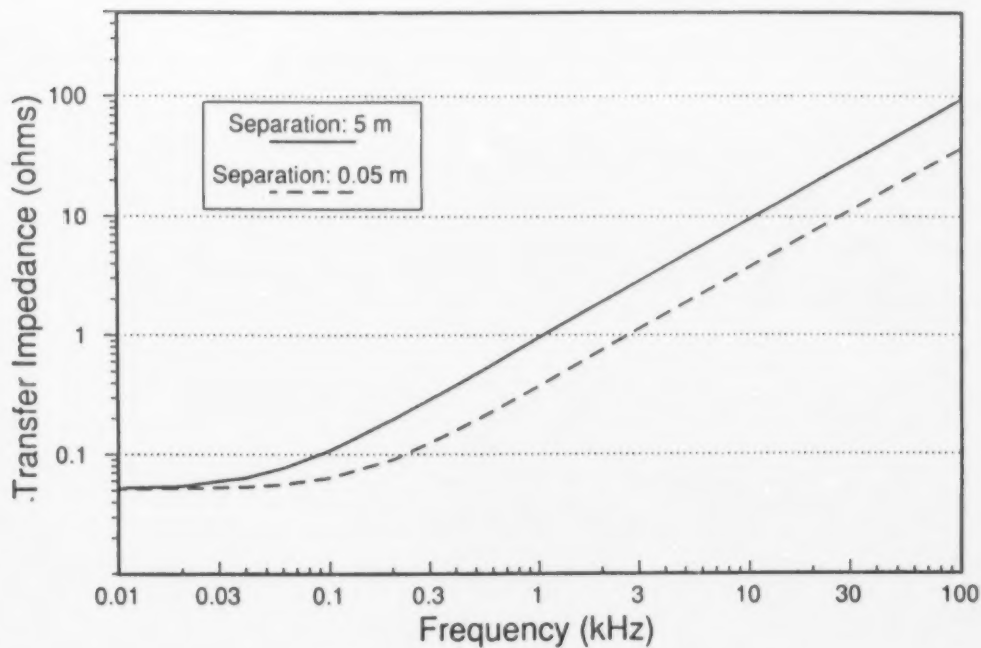


Figure 5 Calculated transfer impedance from Figure 4, for two 100 m long AWG #2 conductors.

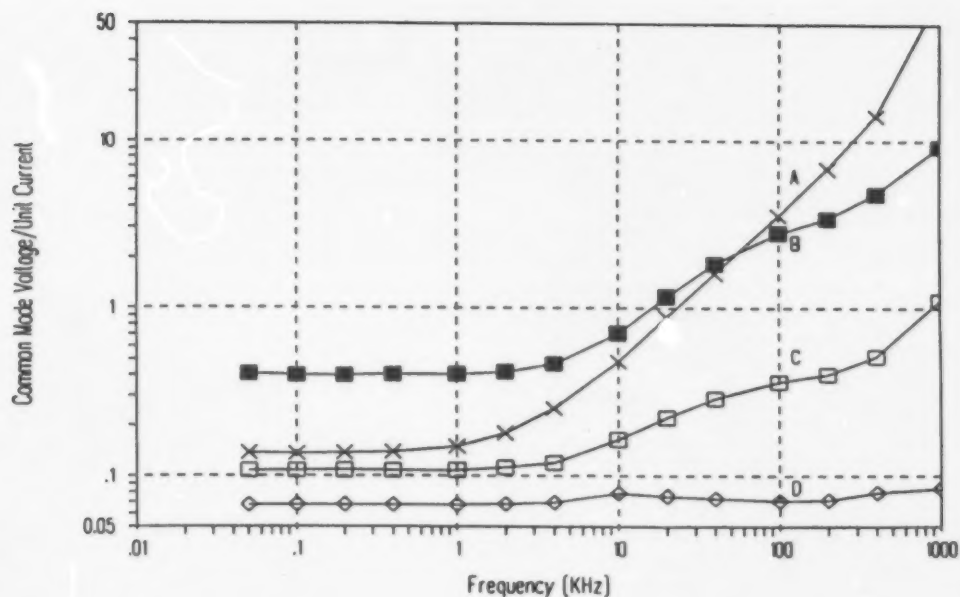


Figure 6 Measured core-to-shield transfer impedance for four 21.5 m long control cable samples. A is a "TECK" armoured cable, B has an aluminized plastic foil shield with drain wire, C has a spiral-wrapped 5-mil (.005 inch) copper tape shield, and D has a corrugated longitudinal 5-mil copper tape shield.

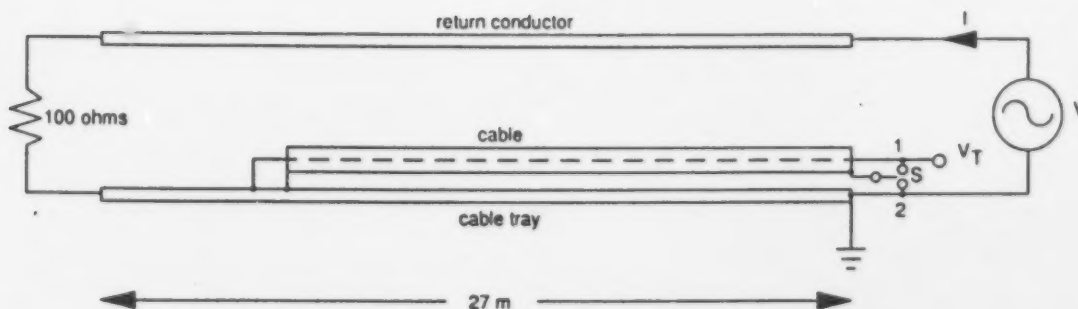


Figure 7 Sketch (not to scale) of resonance response test facility.

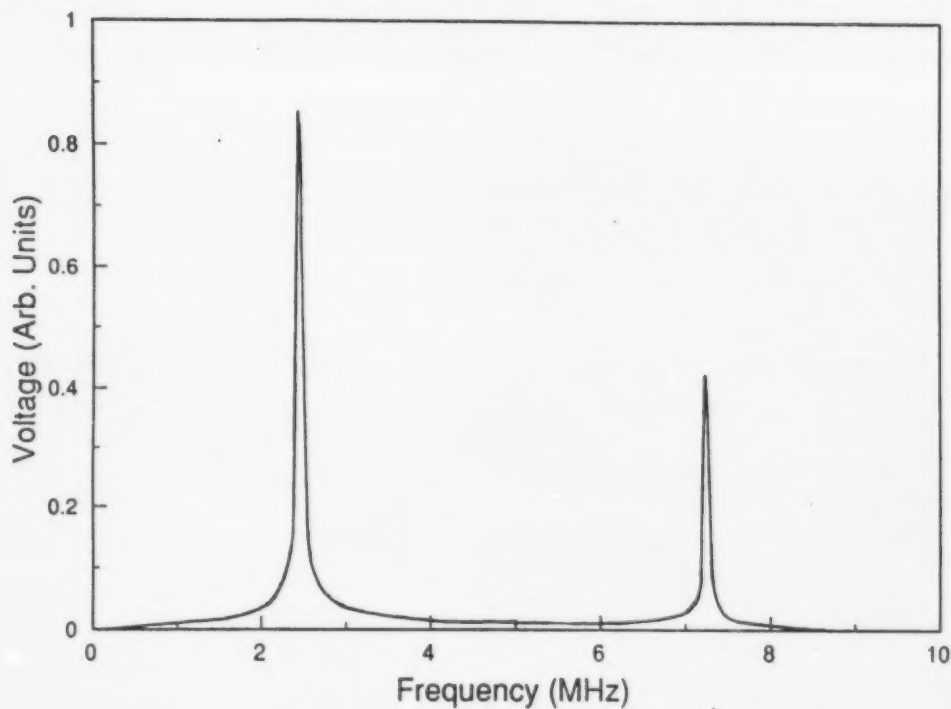


Figure 8 Calculated frequency response of a 21.5 m long transmission line with propagation velocity of 0.7 times free-space velocity.

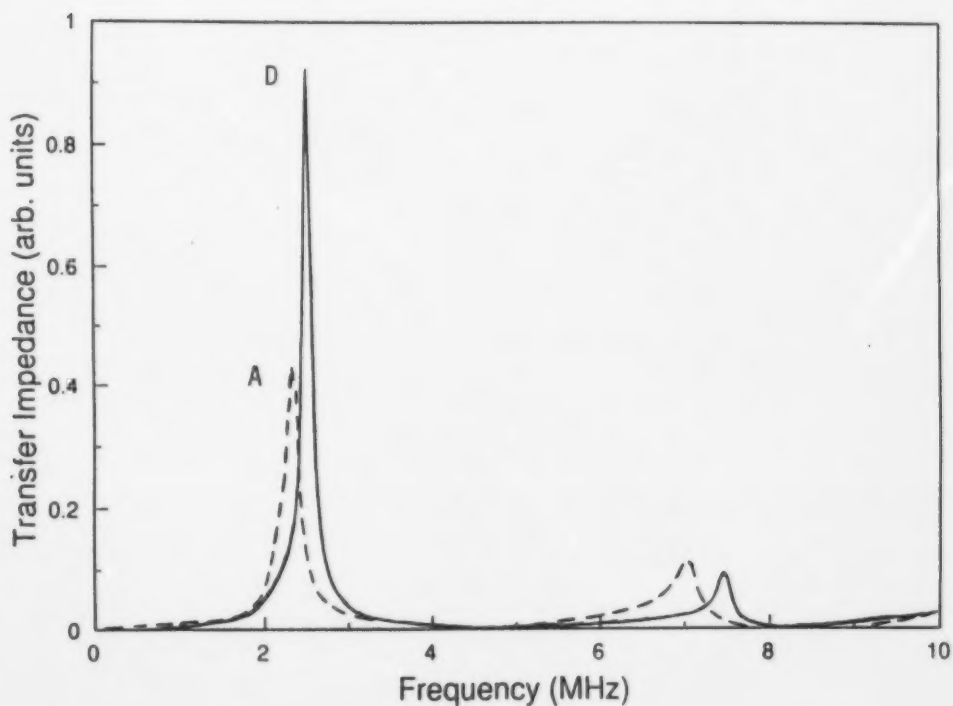


Figure 9 Measured frequency response of cables A and D in the test facility.